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Shows infra-red interference filter curves & describes layer materials & thicknesses

REPORT NO. 2

INTERFERENCE FILTERS FOR THE 8-13 MICRON ATMOSPHERIC WINDOW

by

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SEP 7 1961

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Abstract[1]

Vacuum deposited multi-layer interference filters suitable for isolating broad bands of radiation in the region of the 8-13 micron atmospheric window are described. For example, the spectrophotometric characteristics of a 9 layer flat topped band pass filter on an anti-reflected germanium substrate utilizing alternate quarterwave films of PbTe and half wave films of ZnS are: average T = 90%, half width 3 microns, width at 1% T 4.5 microns, background T = 0.3%. Such a filter centered at 10 microns rejects from 12.5 to 19 microns on one side of the pass band and from 8 to 6.8 microns on the other. Shorter wavelengths may be eliminated by an auxiliary anti-reflected InSb plate, and longer wavelengths by a plate of BaF_2. Variations of these characteristics can be obtained by substituting films of other materials, and by employing different numbers of layers.

[1]Work supported by Engineer Research and Development Laboratory, Fort Belvoir, Virginia.

INTRODUCTION

The infrared transmission spectrum of the earth's atmosphere has a number of regions of relatively high transparency, termed windows. The window lying between the strong absorption bands of water vapor centered at 6 microns and carbon dioxide at 15 microns is of particular interest. This window extends from about 8 to 13 microns and is shown in Figure 1, taken from a paper by R. A. Hanel and W. G. Stroud, "Infrared Imaging From Satellites," J. SMPTE 69, 25 (1960). The abscissae scale is linear in equal increments of energy of a $300^{o}K$ black body with a correspondingly non-linear wavelength scale. This method of plotting is a convenience for rapid estimates of the radiative transfer of energy from the earth into space. For example, it shows directly that a maximum of about 30% of the earth's thermal radiation could escape into space through this window, assuming an average gray body condition for the earth's surface and a temperature near $300^{o}K$. Since the curve is for a vertical path through the atmosphere, the doublet absorption band of ozone, O_3, appears at 9.6 microns. The ozone layer is at a mean height of 22km, hence, its absorption band is not present in atmospheric transmission curves made over a terrestial path.

Filters transmitting the 8-13 micron window region of the spectrum, or selected portions of it, are important both for infrared observations from the earth into space, and for some satellite observations of the earth's surface or its cloud cover. Several materials are available in plate form which transmit in this spectral region and can be used in the construction of filters. Figure 2 gives the spectrophotometric transmittance curves of several of these materials out to 30 microns: arsenic trisulfide glass, As_2S_3, barium fluoride, BaF_2, germanium, Ge, indium antimonide, InSb, indium arsenide, InAs, and irtran, ABC-II.

ABSORPTIVE TYPE FILTERS

A simple filter for the 8-13 micron window utilizes the short wave cutoff at 7.2 microns of a plate of InSb in conjunction with the long wavelength cutoff of As_2S_3, at 13.6 microns. Because of the high refractive indices of these materials, 4.0 and 2.4 respectively, they must be anti-reflected to avoid excessive surface reflectance losses. Plates of InSb used for filters are made as thin as practical because of the high bulk absorption in the commercially obtainable material. In Figure 3 the 0.25mm thick InSb plate was anti-reflected on each face with a quarterwave film of zinc sulfide, ZnS, at 10 microns. This procedure increased the transmittance at this wavelength from 34% to 70% as shown. The plate of As_2S_3 of 1mm thickness was anti-reflected with double coatings, a 0.31 quarter-wave film of lead telluride, PbTe, first being applied followed by a 1.28 quarter-wave film of ZnS, both thicknesses referred to 10 microns. Since films of PbTe show excellent adherence to As_2S_3 substrates, the double anti-reflection coating was designed to incorporate a film of this material. The transmittance gain was from 70% uncoated to 88% coated. Considerable bulk absorption is present in As_2S_3 beyond 8 microns, amounting to 15% at 12 microns for 1mm thickness. This absorption limits the maximum transmittance obtainable. The third curve in Figure 3 is the transmittance of the composite filter comprising the two plates in series. It is mound-shaped, extending from 7.3 to 13.9 microns with a peak transmittance of 61%.

MULTI-LAYER INTERFERENCE FILTERS

A multi-layer interference filter should offer some advantages over the absorptive type. The wavelength limits of the pass band of the interference type can be adjusted for optimum register with the atmospheric window and the inherent high reflectance interval on either side of the pass band of this filter affords some protection against radiative transfer under non-equilibrium conditions between it and other system components, for example, the detector.

The width of the 8-13 micron window excludes the more usual band pass filter designs which generally result in a half width to peak wavelength ratio of 2 to 12%, whereas a 47% ratio is needed to span the window. Figures 4 and 5 are typical examples of these band pass filters for the 10 micron region. Figure 4 is the measured transmittance curve of a narrow band 7-layer filter centered at 10.6 microns with a peak transmittance of 74% and a half width ratio of 1.6%. The filming materials are PbTe for the high index films and ZnS for the low. The free filter range, FFR, of a filter is defined for practical purposes as the wavelength interval outside of which there is more than 1% leakage of unwanted radiation where auxiliary filtering is required. Here the FFR extends from 7.9 microns indefinitely toward longer wavelengths because of absorption in the BaF_2 substrate.

Figure 5 gives the measured transmittance curve of a 9-layer square-topped band pass filter with the same filming materials in a design yielding a half width ratio of 11.8%. The nine films were deposited on a 0.5mm thick plate of As_2S_3 to each face of which first was applied the double anti-reflection coating of PbTe and ZnS described above and formulated as G(0.31H) (1.28L)A. Film thicknesses were adjusted to center the pass band at 8.9 microns. The peak transmittance is 80% and the FFR extends from 6.7 microns indefinitely toward longer wavelengths.

These filters and filters having related designs may be used to select different portions of the 8-13 micron window by an appropriate choice of film thicknesses to locate the pass bands at the desired wavelengths. In general, auxiliary filters are required to prevent radiation leakage beyond the FFR limits, in particular toward shorter wavelengths. Substrate absorption often suffices toward longer wavelengths.

As a basis for the design of a very broad pass band filter advantage is taken of the high reflectance band properties of a multi-layer structure made up of a number of identical periods. Except in special cases, high reflectance bands appear in the spectrum where the optical thickness of an individual period is an integral multiple of one-half wavelength. With a sufficient number of periods the reflectance within these bands approaches unity as closely as desired. Between the bands is a window region throughout which the transmittance is high, in effect the pass band of a filter. Available filming materials permit the construction of a filter in this way. The pass band of such a filter closely coincides with the limits of the 8-13 micron atmospheric window.

In considering the period LHL, Figure 6, let L represent a film of ZnS, of refractive index 2.2 and optically one quarterwave thick at an arbitrary reference frequency w = 30. Let H represent a film of PbTe of index 5.1 and optically one quarterwave thick at the same reference frequency. At w = 20 the total period thickness is one-half wave, at w = 40 it is one full wave. Consequently, regions of increasingly high reflectance or high reflectance bands, HRB, will develop around these frequencies as more periods are added. Between the bands is a gap in which the reflectance remains low and the transmittance high, i.e., the pass band region. The frequency limits of this gap for the ZnS/PbTe/ZnS construction are w = 35.8 and 24.2 having a ratio 1.48. This is not sufficient to span the 8-13 micron window which requires a frequency or wavelength ratio of 1.63.

A wider gap is obtained by selecting a pair of films with a smaller ratio of refractive indices than above. This narrows the high reflectance bands which must remain centered, at the same frequency positions, w = 20 and 40. Conse-

DIVISION 7

SEP 7 1961

U. S. PATENT OFFICE

quently, the gap between them widens. The lower curves in Figure 6 are for the same period construction (LHL) but using stibnite, Sb_2S_3, of refractive index 2.7 in place of ZnS. The frequency limits of the gap now lie at w = 36.8 and 23.2 with a ratio of 1.59, a value satisfactorily close to the frequency span of the atmospheric window.

A symmetrical period as used here has an equivalent Herpin index, (N), which is real outside the HRBs. A multi-layer structure composed of any number of periods behaves as a thick film of index N. This equivalent index varies rapidly with frequency, as shown in Figure 6 where its value is plotted between the HRBs for each case. Its maximum value here is given by n_L^2/n_H where n_L is the refractive index of the L film and n_H that of the H. This maximum value is 0.95 for the ZnS/PbTe/ZnS period and 1.43 for the Sb_2S_3/PbTe/Sb_2S_3 period. These values serve as guides in selecting substrates best matched to the filter coatings to minimize the interference oscillations between the HRBs and secure maximum transmittance over a relative flat-topped pass band.

The refractive index of BaF_2 at 10 microns is 1.42, an almost perfect match for the Sb_2S_3/PbTe film combination. Throughout the frequency range from w = 36 to 24, the Herpin equivalent index, (N), lies between air, n = 1.0, and the substrate index, n = 1.43, with the exception of a short interval near w = 30. Consequently, over almost all of its pass band, the transmittance of the filter will be equal to or greater than that of the uncoated BaF_2 (single surface T = 97%) independent of the number of periods used.

The selection of a substrate for a filter coating having ZnS/PbTe/ZnS periods follows a similar argument. The maximum value of N is 0.95 so this filter combination on BaF_2 will have deeper interference transmittance minima

in the pass band than the first. A substrate of still lower index is indicated and can be simulated at one wavelength by Ge anti-reflected with a quarterwave film of ZnS. This combination has a load admittance $Y = \frac{2}{2.2/4.0} = 1.21$ at $w = 30$. However, the gain in transmittance here amounts only to 3% and in practice either substrate is satisfactory.

Figure 7 shows the measured transmittance of an 11-layer ZnS/PbTe filter on a substrate of Ge which was anti-reflected first on each face with a film of ZnS one quarterwave thick at 11.3 microns. The peak transmittance is over 90% and the half power points lie at 9.7 and 13.4 microns, giving a half width ratio of 33%. The FFR extends to 7.9 microns on the short wavelength side with a measured minimum transmittance of 0.3%. On the long wavelength side there is 10 or 15% leakage from 22 - 28 microns.

The short wavelength edge of the pass band of this example was located to just reject the O_3 absorption band at 9.6 microns. If the thermal emission from this band was harmful in observations through the atmospheric window, it could be avoided with a filter of this description, although a still narrower pass band might be desirable to exclude also all the thermal emission from the carbon dioxide band on the long wavelength side.

In Figure 8 the upper curve is the measured transmittance of the wider filter obtained by replacing the ZnS with Sb_2S_3 in the same coating design. Six periods were used to give a 13-layer coating on a substrate of BaF_2. The peak transmittance of the filter is 90% and the half power points are at 8.1 and 12.2 microns, giving a half width ratio of 42%. Due to absorption in the BaF_2 substrate, the FFR extends indefinitely toward longer wavelengths. Toward shorter wavelengths, the FFR terminates at 6.9 microns and auxiliary filtering is required.

LOW PASS AUXILIARY FILTERS

An anti-reflected plate of InSb may be used for the purpose of eliminating higher order bands at shorter wavelengths. The measured transmittance of such a composite filter is shown as the lower curve in Figure 8. Losses in the InSb component cut the maximum transmittance of the complete composite filter to 63% from the original 90%.

A more efficient auxiliary is a low pass filter utilizing films of PbTe and chiolite, $5NaF \cdot 3AlF_3$. In Figure 9, upper curve, six periods of the form 0.5H(L)0.5H were employed as the filter coating on a BaF_2 substrate. This period in which the H film index is 5.1 and the L film index 1.35, as assumed for the PbTe and chiolite respectively, produces a first order high reflectance band the frequency or wavelength limits of which are in a ratio of 2.3, the theoretical FFR. Experimentally the 6-period construction resulted in a FFR having 1% transmittance limits between 6.8 and 3.1 microns, a ratio of 2.2. The lower wavelength lies in the strongly absorbing region of the PbTe which begins at 4 microns.

In order to eliminate strong secondary interference transmittance minima in the 8-13 micron pass region, both sides of the low pass filter coating were anti-reflected at 10 microns by double film combinations of ZnS and chiolite, the thicknesses of which are given in Figure 8. It should be noted that the thickness parameters are different for the air and for the substrate side of the low pass filter coating, but details of the design principles will be reserved for another report. The total number of layers in this auxiliary is 17, and they are deposited on one face of the BaF_2 substrate plate with the 13-layers of the window pass band filter on the other to form a composite filter. Measured transmittance of this composite filter is reproduced as the second curve in

Figure 8. A maximum transmittance of 88% is obtained; the half power points lie at 8.1 and 12.1 microns and the 1% transmittance points at 7.8 and 12.9 microns. The FFR extends indefinitely in both directions due to the strong absorption in the PbTe films below 3 microns and in the BaF_2 substrate above 17.5 microns.

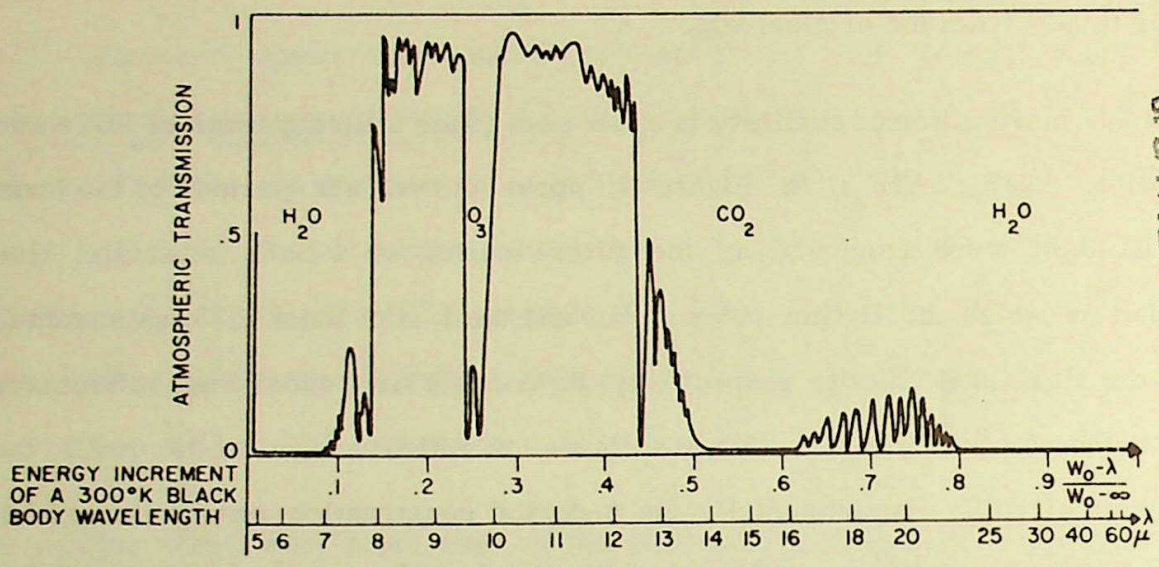

FIGURE 1

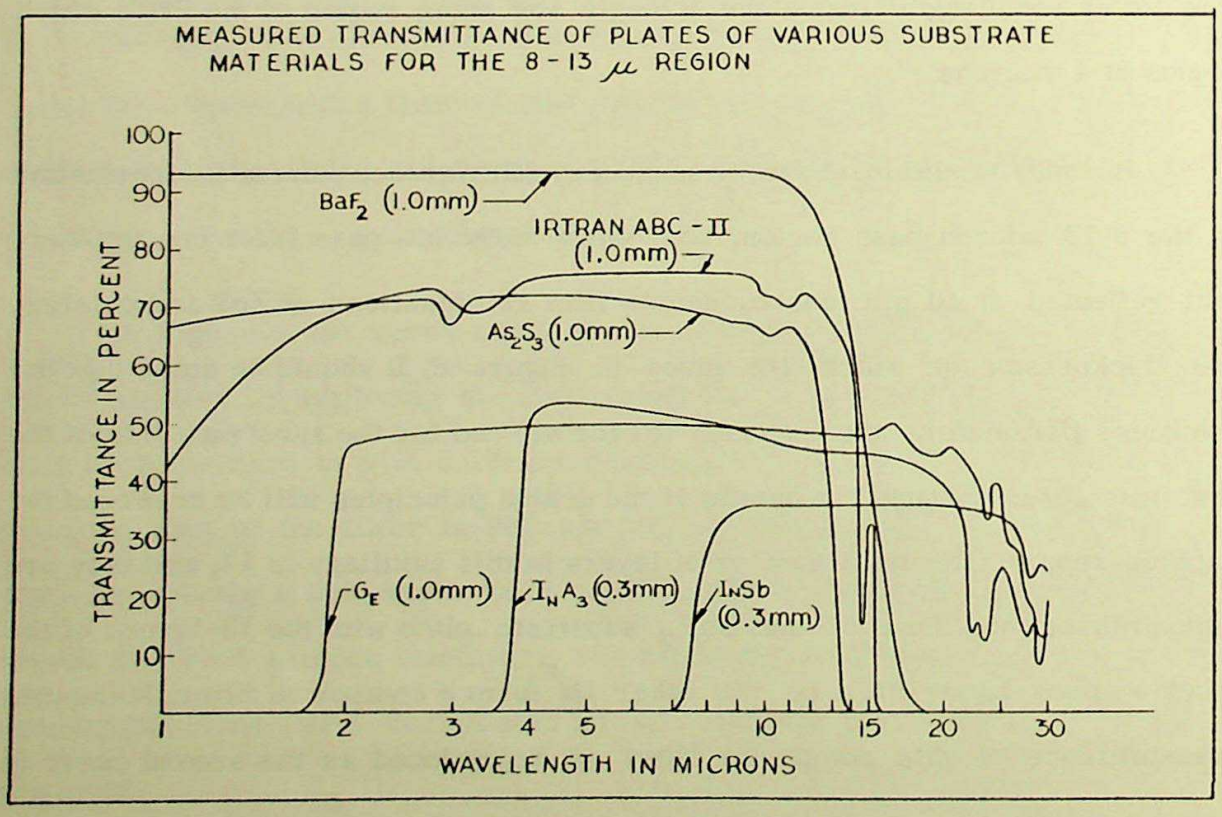

FIGURE 2

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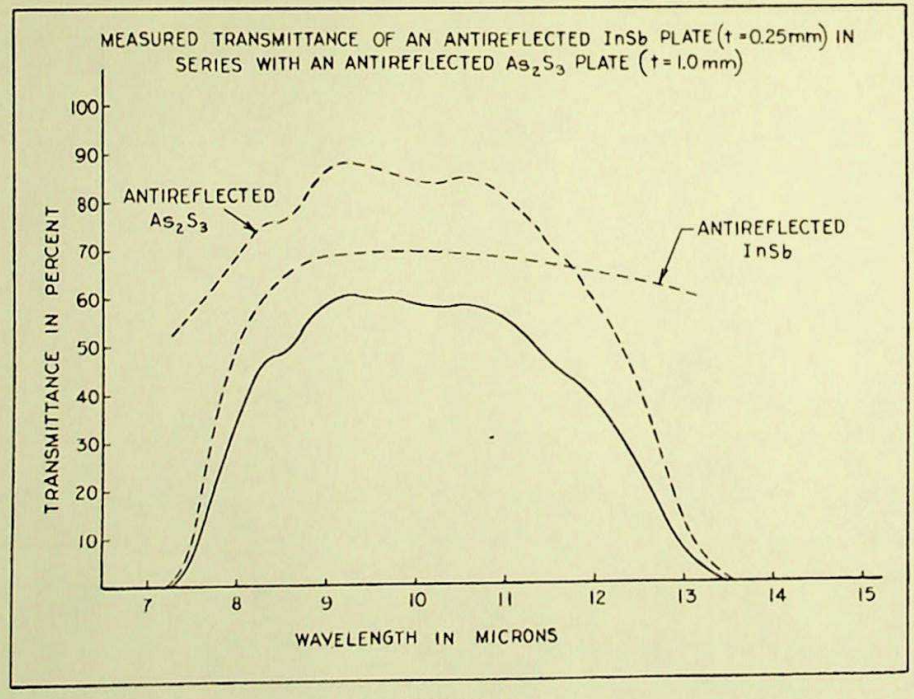
MEASURED TRANSMITTANCE OF AN ANTIREFLECTED InSb PLATE (t = 0.25mm) IN SERIES WITH AN ANTIREFLECTED As_2S_3 PLATE (t = 1.0 mm)
ANTIREFLECTED As_2S_3
ANTIREFLECTED InSb
TRANSMITTANCE IN PERCENT
WAVELENGTH IN MICRONS

FIGURE 3

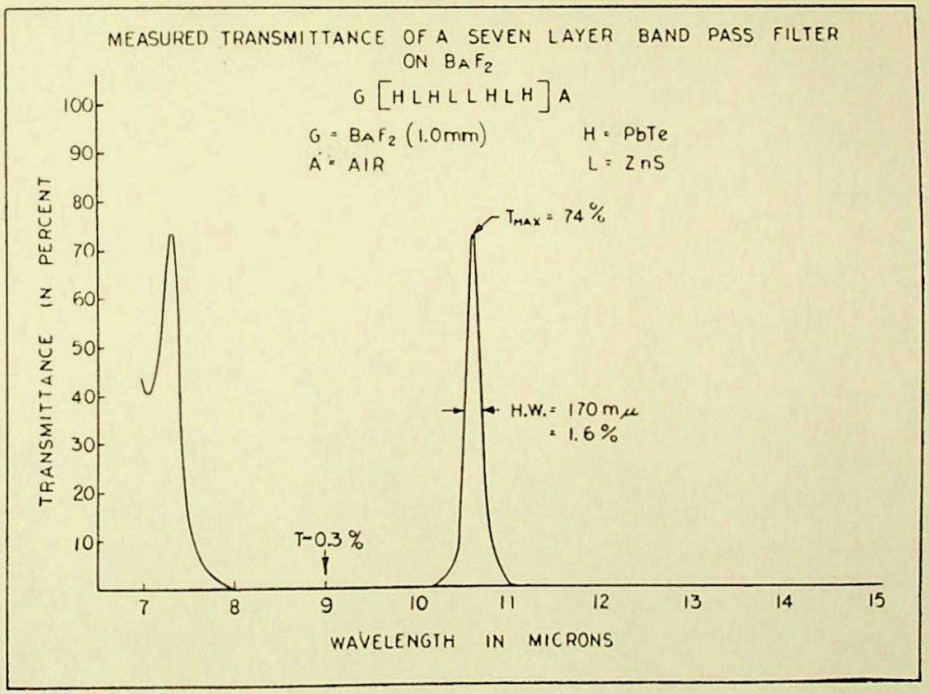
MEASURED TRANSMITTANCE OF A SEVEN LAYER BAND PASS FILTER ON BaF_2
G [H L H L L H L H] A
G = BaF_2 (1.0mm)
A = AIR
H = PbTe
L = ZnS
T_{MAX} = 74 %
H.W. = 170 mμ = 1.6 %
T = 0.3 %
TRANSMITTANCE IN PERCENT
WAVELENGTH IN MICRONS

FIGURE 4

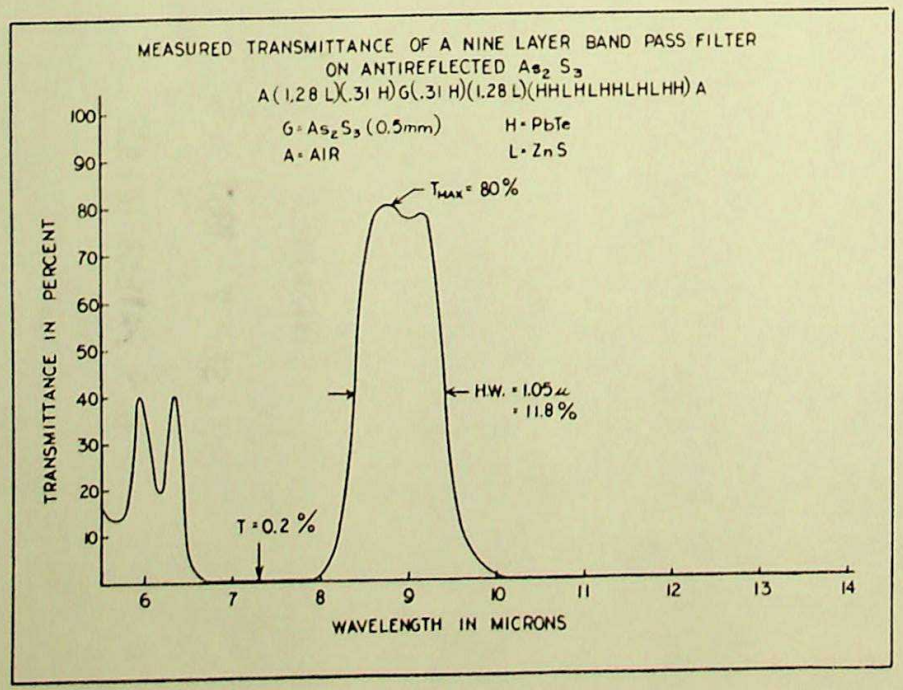
MEASURED TRANSMITTANCE OF A NINE LAYER BAND PASS FILTER ON ANTIREFLECTED As_2S_3
A (1.28 L)(.31 H) G (.31 H)(1.28 L)(HHLHLHHLHLHH) A
G = As_2S_3 (0.5mm)
A = AIR
H = PbTe
L = ZnS
T_{MAX} = 80 %
H.W. = 1.05 μ = 11.8 %
T = 0.2 %
TRANSMITTANCE IN PERCENT
WAVELENGTH IN MICRONS

FIGURE 5

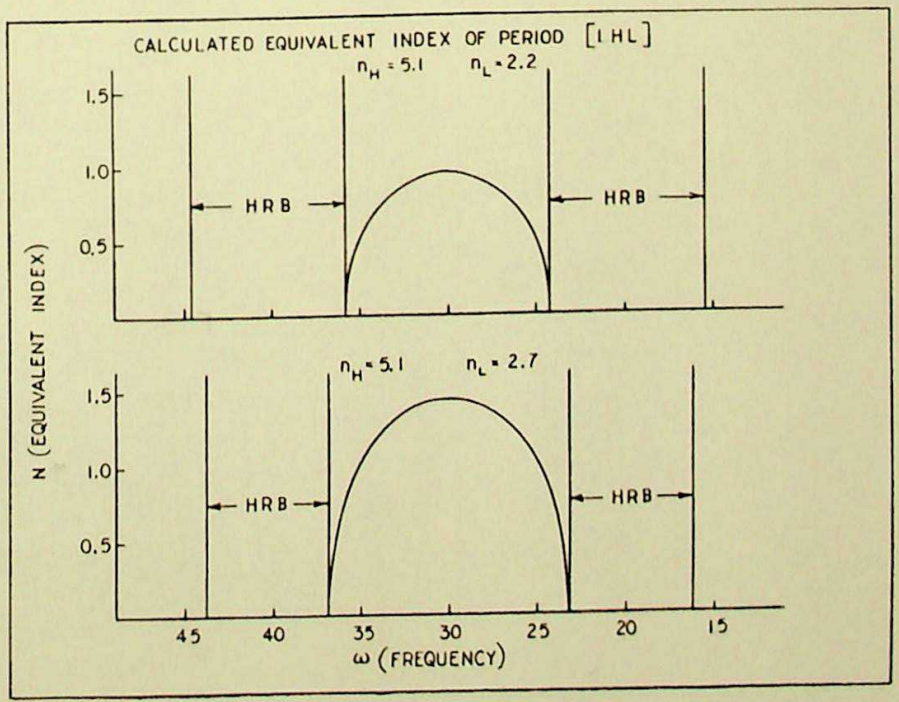

FIGURE 6

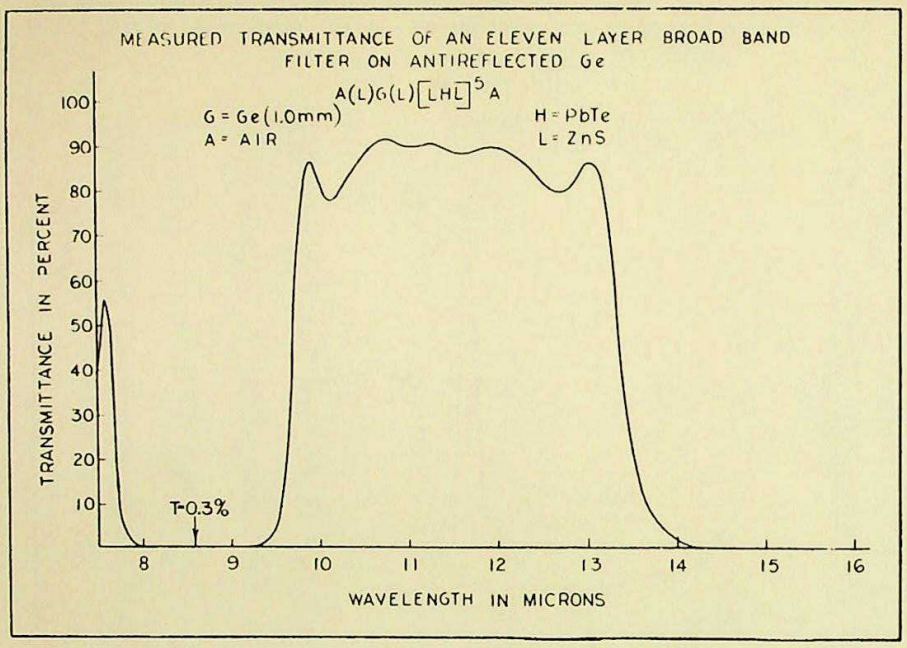

FIGURE 7

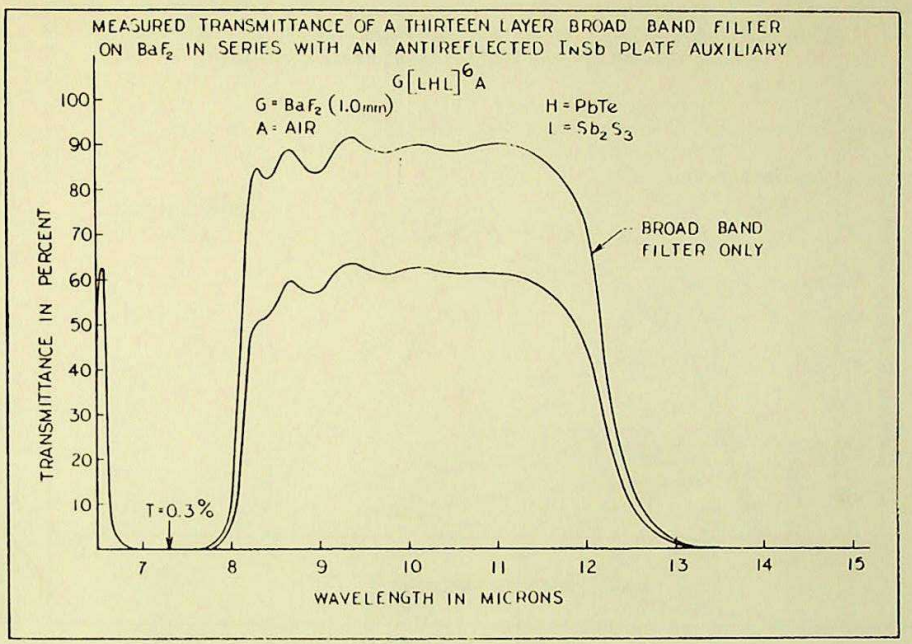
MEASURED TRANSMITTANCE OF A THIRTEEN LAYER BROAD BAND FILTER ON BaF2 IN SERIES WITH AN ANTIREFLECTED InSb PLATE AUXILIARY
G[LHL]^6 A
G = BaF2 (1.0mm)
A = AIR
H = PbTe
L = Sb2S3
BROAD BAND FILTER ONLY
T=0.3%
TRANSMITTANCE IN PERCENT
WAVELENGTH IN MICRONS

FIGURE 8

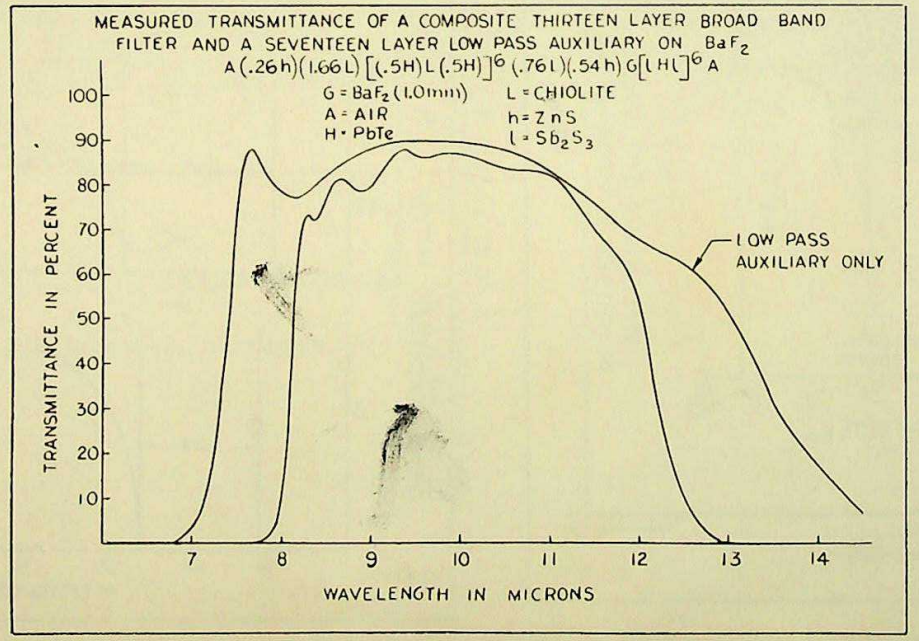
MEASURED TRANSMITTANCE OF A COMPOSITE THIRTEEN LAYER BROAD BAND FILTER AND A SEVENTEEN LAYER LOW PASS AUXILIARY ON BaF2
A(.26h)(1.66L)[(.5H)L(.5H)]^6 (.76L)(.54h) G[LHL]^6 A
G = BaF2 (1.0mm)
A = AIR
H = PbTe
L = CHIOLITE
h = ZnS
l = Sb2S3
LOW PASS AUXILIARY ONLY
TRANSMITTANCE IN PERCENT
WAVELENGTH IN MICRONS

FIGURE 9

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